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**Assessment of physical function following total hip arthroplasty:
inertial sensor based gait analysis is supplementary to patient-reported outcome measures**

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Highlights:

- Gait analysis and self-reported function are moderately correlated after total hip arthroplasty;
- Gait analysis captures post-operative improvement beyond 3 months in follow-up;
- Gait analysis is less sensitive to detect changes in patients with high pre-operative function;
- One year after total hip arthroplasty, lower walking speed and smaller steps are still observed;
- Comprehensive functional outcome assessment includes both relative and absolute changes.

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Keywords: gait, inertial sensor, total hip arthroplasty, outcome assessment, PROM, WOMAC.

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Abstract

Background: Functional outcome assessment after total hip arthroplasty often involves subjective patient-reported outcome measures whereas analysis of gait is more objective. The study's aims were to compare subjective and objective functional outcomes after total hip arthroplasty between patients with low and high self-reported levels of pre-operative physical function.

Methods: Patients undergoing total hip arthroplasty (n=36; m/f=18/18; mean age=63.9; SD=9.8yrs; BMI=26.3 SD=3.5) were divided into a low and high function subgroup, and prospective measures of WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index) function score and gait were compared at baseline and 3 and 12 months post-operatively.

Findings: WOMAC function scores significantly improved in both low and high function subgroups at 3 months post-operatively whereas gait parameters only improved in patients with a low pre-operative function. Between 3 and 12 months post-operatively, WOMAC function scores had not significantly further improved whereas several gait parameters significantly improved in the low function group. WOMAC function scores and gait parameters were only moderately correlated (Spearman's $r = 0.33-0.51$).

Interpretation: In a cohort of patients undergoing total hip arthroplasty, pre-operative differences in mean WOMAC function scores and gait parameters between low and high function subgroups disappeared by 3 months post-operatively. Gait parameters only improved significantly during the first 3 post-operative months in patients with a low pre-operative function, highlighting the importance of investigating relative changes rather than the absolute changes and the need to consider patients with high and low function separately.

Keywords: gait, inertial sensor, total hip arthroplasty, outcome assessment, PROM, WOMAC.

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1. Introduction

Total hip arthroplasty (THA) is one of the most frequently performed and successful reconstructive procedures in orthopedic surgery, with more than one million procedures undertaken every year worldwide [1]. Because of an ageing population and the increase in obesity, the incidence of osteoarthritis (OA) and the number of THA's is expected to increase substantially in future decades [2]. Although the majority of THAs are provided to patients aged 65 years and older, the proportion of patients younger than 65 years is projected to increase to 50% of all arthroplasties by 2030 [3]. With a growing and more active older population, and an increasing number of younger patients undergoing THA, the functional demands expected of THA will change and assessment of outcomes will equally need to evolve [3, 4]. Assessment of outcomes after THA often involves patient-reported outcome measures (PROMs) focusing mainly on two domains: pain and function. PROMs are widely used in research and clinical settings, and they are considered easy to use, inexpensive and time efficient. One of the most commonly used PROMs is the disease-specific Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) which has been validated for use with patients undergoing THA [5, 6]. Following THA, patients who are more satisfied are also more likely to have higher total WOMAC scores with the amount of improvement depending on baseline status [7]. Furthermore, it has been demonstrated that patients with lower pre-operative self-reported WOMAC function scores do not improve their final outcomes to the same magnitude as patients with higher pre-operative scores [8]. However, WOMAC scores represent subjective self-reported measures which are easily influenced by socioeconomic or psychological factors and dominated by pain [9, 10]. Moreover, as with many orthopedic PROMs, the WOMAC score suffers from a ceiling effect as it has a limited maximum value that is reached by a substantial proportion of patients who report no pain or functional limitations after THA [11-13]. A consequence of this ceiling effect is that the true extent of patients' post-operative functional abilities cannot be determined. Therefore, it is important that research considers other methods of assessing functional outcomes after THA. Gait analysis has widely been accepted as an objective measure of physical function, allowing researchers and clinicians to better understand biomechanical alterations in the presence of hip osteoarthritis (OA) and to evaluate the functional success of THA and rehabilitation strategies [13-15]. However, the gold standard for clinical gait analysis, an optoelectronic motion capture (MOCAP) system, is time consuming and expensive, requires a specially

equipped laboratory and it is limited to a specific motion capture volume, constrained by space and equipment. As an alternative to these sophisticated but clinically unfeasible MOCAP systems, ambulant accelerometers have developed into reliable tools for the assessment of basic spatiotemporal gait parameters (e.g. cadence, step length) which can discriminate healthy subjects from OA patients [14, 16] and have demonstrated responsiveness to post-operative changes [17]. More recently, inertial sensors (i.e. accelerometer combined with a gyroscope) have been validated for kinematic measurements of gait [18, 19], such as joint range of motion (ROM), and could provide more detailed information on gait disturbances in hip OA patients outside the gait laboratory [20]. Given the differences in self-reported functional outcomes between patients with low and high pre-operative function, it is important to establish if these patterns of recovery are also observed with objective measures of physical function [21, 22].

The primary aim of the study was to compare the longitudinal changes in physical function between hip OA patients with a low and high self-reported level of physical function, from just prior to THA until one year post arthroplasty, assessed by a subjective patient-reported outcome measure (WOMAC function score) and an objective functional measurement (inertial sensor based gait analysis). A second aim of the study was to compare the trajectories of post-operative recovery between the WOMAC function score and gait parameters. The third aim was to compare the outcomes of gait analysis one year after THA from our cohort with those of a healthy control group. We expected that patients with a low pre-operative WOMAC function score would also demonstrate worse post-operative WOMAC function scores [8], but hypothesized that these differences may not be found with objective gait parameters as they are less influenced by socioeconomic and psychological factors [9] and weak to moderate correlations between PROMs and performance-based tests have been reported in the literature [6, 10, 17, 23, 24]. We further hypothesized that WOMAC function scores and gait parameters would demonstrate distinct post-operative recovery patterns, as for WOMAC function scores a larger change in the first 3 months and a smaller change in the following 9 months was anticipated because they are more likely influenced by ceiling effects [9, 10]. Finally, we hypothesized that gait performance in patients one year after THA would still be slightly worse compared to healthy controls [25].

2. Methods

2.1 Study and participants

The patient data used in this analysis were from a single center prospective UK cohort study comparing functional measures in patients undergoing joint replacement (the ADAPT study). A detailed description has been reported previously [26]. From this cohort, patients listed for primary THA were selected. Patients completed the WOMAC questionnaire and their gait was assessed pre-operatively (mean=24 days; SD=13 days), at 3 months (mean=106 days; SD=19 days) and at 12 months (mean=385 days; SD=22 days) post-operatively. Patients with missing data at any assessment time, either from the WOMAC questionnaire or from gait analysis, were excluded from this analysis. This resulted in a study population of 36 patients (m/f=18/18; mean age=63.9; SD=9.8yrs; BMI=26.3 SD=3.5). A control group of individuals (n=30; m/f=18/12; mean age=61.0years; SD=5.6; mean BMI=24.8; SD=2.8) without joint pain and without a medical history of lower extremity joint surgery was used to compare post-operative outcomes [27].

2.2 Patient-reported outcome assessment

The WOMAC score is designed to provide information on a patient's perception of pain (5 items), stiffness (2 items) and physical function (17 items). The function dimension of the total WOMAC score (i.e. WOMAC function score) was used in this analysis. The WOMAC function score contains 17-items and each item is scored on a 5-point ordered response scale. The score was transformed to a 0-100 score, with 0 representing the lowest (i.e. worst) score and 100 representing the highest (i.e. best) score [23].

2.3 Gait test protocol

Participants were invited to walk 20 meters along a straight flat corridor at their own preferred speed [27, 28]. A 3D inertial sensor (41x63x24mm; 39g; Microstrain Inertia Link) was used, containing gyroscopes ($\pm 300^\circ/\text{s}$) and accelerometers ($\pm 5\text{g}$) along orthogonal axes in frontal, sagittal and transverse plane. The sensor was attached onto the skin with a neoprene strap, and positioned centrally between the posterior superior iliac spines (PSIS) overlying S1 [27]. Data analysis was performed using algorithms in Matlab2009a to detect heel strike (HS) events during gait from the raw antero-posterior (AP) acceleration

signal to derive spatiotemporal gait parameters [29], including 1) walking speed ($\frac{\text{distance covered}}{\text{time}}$; m/s), 2) cadence ($60 * \frac{\text{step count}}{\text{time}}$; steps/min), 3) step time (s), 4) step length ($\frac{\text{distance covered}}{\text{step count}}$; m); 5) step time irregularity ($\frac{SD}{\text{mean}}$; coefficient of variance) and 6) step time asymmetry ($100\% * \frac{(\text{abs}(\text{left step times} - \text{right step times}))}{(0.5 * (\text{left step times} + \text{right times}))}$; %). The sensor's inbuilt integration of the gyroscope signals provided static and dynamic orientation angles, allowing additional kinematic characterization of the pelvis during gait. The range of motion (ROM; degrees) of the pelvis in frontal plane (i.e. pelvic obliquity) was calculated [27] as it is related to impairment of hip abductor muscles in patients with hip OA [30-32] which may persist following THA [33].

2.4 Statistical analysis

Pre-operative WOMAC function score was dichotomized according to median threshold to define low and high function groups. Linear mixed models (LMM) in Stata13 were used to investigate longitudinal trends of changes post-operatively in the low and high function groups with p-values <0.05 as significance threshold. Self-reported WOMAC function scores and objective gait measures are described for each measurement point with median and interquartile range (IQR), between 25th and 75th percentile, because of the non-normal distribution of the post-operative data. Comparison of both self-reported WOMAC function scores and gait measures between low and high function groups was conducted with Mann-Whitney U tests. Linear mixed models with random intercept and slope (on period's indicators) were used to assess the magnitudes of change between pre-operative and 3 months post-operative, and between 3 and 12 months post-operative. These changes were normally distributed and results are reported by the mean and 95% confidence interval (CI). The magnitudes of change (i.e. slope of curve) for WOMAC function scores and gait parameters between the first 3 post-operative months and the following 9 post-operative months were quantified as averaged change per month (mean; 95% confidence interval; p-value) and outcomes were compared between low and high function groups within the LMM framework. Correlations between WOMAC function scores and gait parameters were calculated with the Spearman's correlation coefficient and interpreted as follows: <0.2: none; 0.21-0.5 weak; 0.51–0.8: moderate; >0.81: strong [34].

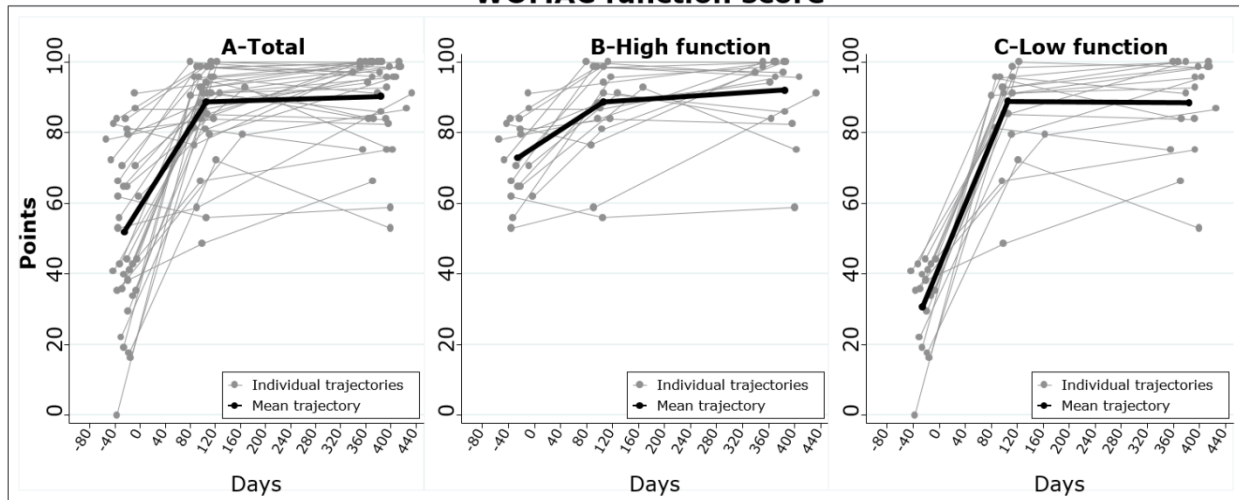
3. Results

Pre-operatively, the median WOMAC function score was 49 (IQR=36-71). Using this median as a cut-off, two subgroups were formed: a low function group (n=18) with a pre-operative median WOMAC function score of 36 (IQR=22-41) and a high function group (n=18) with a significantly higher pre-operative median WOMAC function score of 71 (IQR=65-82) ($p<0.001$). In gait, significant differences were also found between the low and high function groups for the parameters speed (0.89 vs. 1.10m/s; $p=0.006$), step length (0.50 vs. 0.60m; $p=0.003$) and ROM pelvic obliquity (4.7 vs. 6.0°; $p=0.015$) (table 1). In addition, significant but weak to moderate correlations were found between the pre-operative WOMAC function scores and gait parameters speed (Spearman's $r=0.51$; $p=0.002$), step length (Spearman's $r=0.47$; $p=0.004$) and ROM (Spearman's $r=0.43$; $p=0.010$) (table 2).

At 3 months post-operatively, WOMAC function scores had significantly improved for the total patient group (median=92; IQR=81-96; $p<0.001$), for the low function group (median=91; IQR=79-96; $p<0.001$) and high function group (median=91; IQR=84-99; $p<0.001$); (table 1; figure 1). Furthermore, 18 of 36 patients (50%) reached near-maximum (≥ 90) WOMAC function scores at 3 months post-operatively (figure 1). No significant difference in WOMAC function score was observed between the low function group and the high function group at 3 months post-operatively. The magnitude of change for WOMAC function scores during the first 3 post-operative months was significantly higher for patients from the low function group compared to patients from the high function group (averaged change per month = 13.31 vs. 3.59 points respectively; $p<0.001$; table 3). Gait parameters in the total patient group had also improved significantly 3 months after THA, except for step time irregularity and step time asymmetry (table 1). Sub group analysis demonstrated that the gait parameters only significantly improved in patients from the low function group and comparing the magnitudes of change (i.e. averaged change per month) during the first 3 post-operative months between the low and high function group demonstrated significant differences for the gait parameters: speed (0.060 vs. 0.011m/s resp.; $p=0.007$), cadence (2.64 vs. 0.35steps/min resp.; $p=0.03$), step time (-0.019 vs. -0.002s resp. $p=0.039$), step length (0.023 vs. 0.04m resp.; $p=0.009$) and ROM (0.43 vs. 0.18° resp.; $p=0.008$) (figure 1, table 3). At 3 months post-operatively, patients from the low function group reached a level of walking ability comparable to patients from the high function group as median values of gait parameters were not significantly different anymore. No significant correlation for any of the gait parameters with WOMAC function score was found at 3 months post-operatively (table 2).

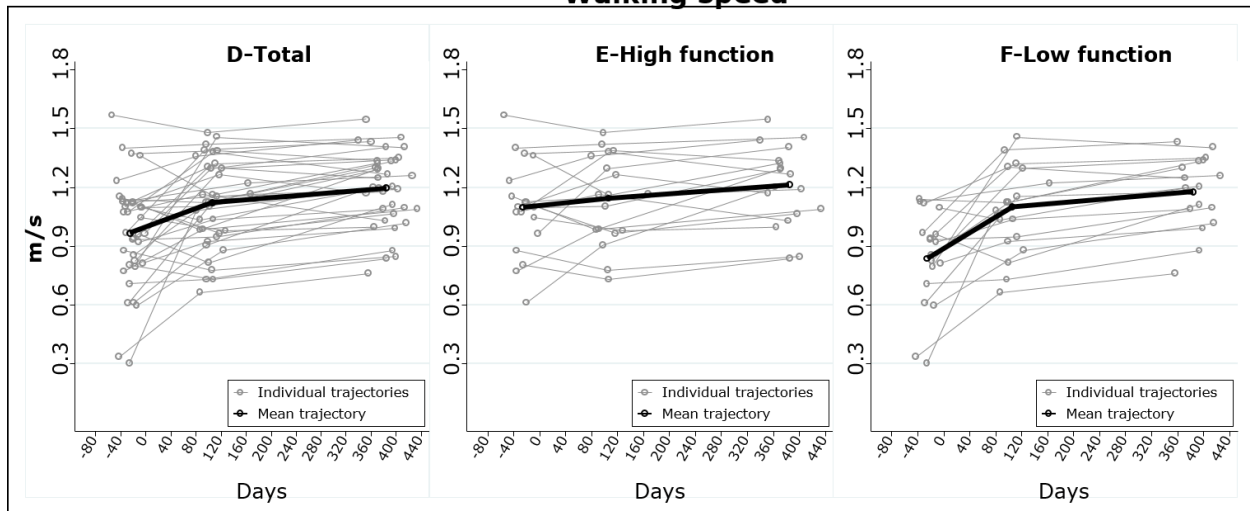
137 At 12 months post-operatively, WOMAC function scores were not significantly different to WOMAC function
138 scores measured at 3 months post-operatively in the total group, nor in the low and high function groups
139 (table 1). In addition, 23 of 36 patients (64%) reached near-maximum (≥ 90) WOMAC function scores and
140 10 of 36 patients (28%) reported the maximum WOMAC function score of 100 at 12 months post-
141 operatively. Between 3 and 12 months post-operatively, speed and step length significantly improved in the
142 total patient group (table 1; figure 1). Separate subgroup analysis demonstrated that the observed
143 improvement was only found in patients with a low pre-operative self-reported function. However, no
144 differences were found for gait parameters at 3 and at 12 months post-operatively between the high and
145 low function groups (table 1) and the averaged change per month between 3 and 12 months post-
146 operatively showed no significant differences between the low and high function groups (table 2). At 12
147 months post-operatively, weak correlations were found between the WOMAC function score and the gait
148 parameters speed (Spearman's $r=0.45$; $p=0.005$), cadence (Spearman's $r=0.37$; $p=0.027$), step time
149 (Spearman's $r=0.37$; $p=0.027$), ROM (Spearman's $r=0.51$; $p=0.002$), step time irregularity (Spearman's $r=-$
150 0.39 ; $p=0.018$) and step time asymmetry (Spearman's $r=-0.33$; $p=0.047$). At 12 months post-operatively,
151 the THA cohort approached the level of the control group comparing gait parameters, except for speed
152 (1.20 vs. 1.29m/s; $p=0.036$) and step length (0.64 vs. 0.68m; $p=0.004$) (table 1).

WOMAC function score



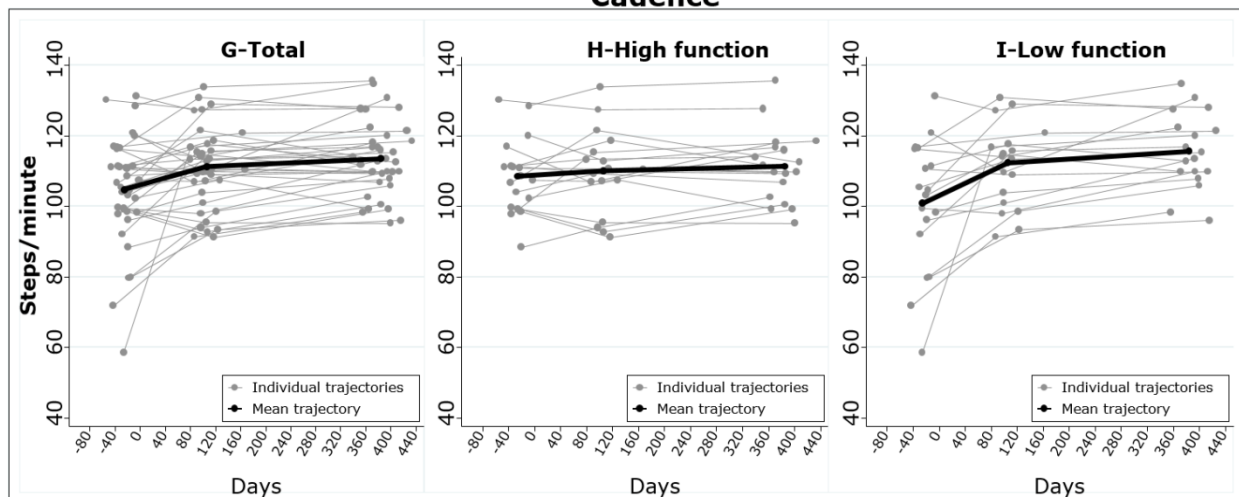
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Walking speed

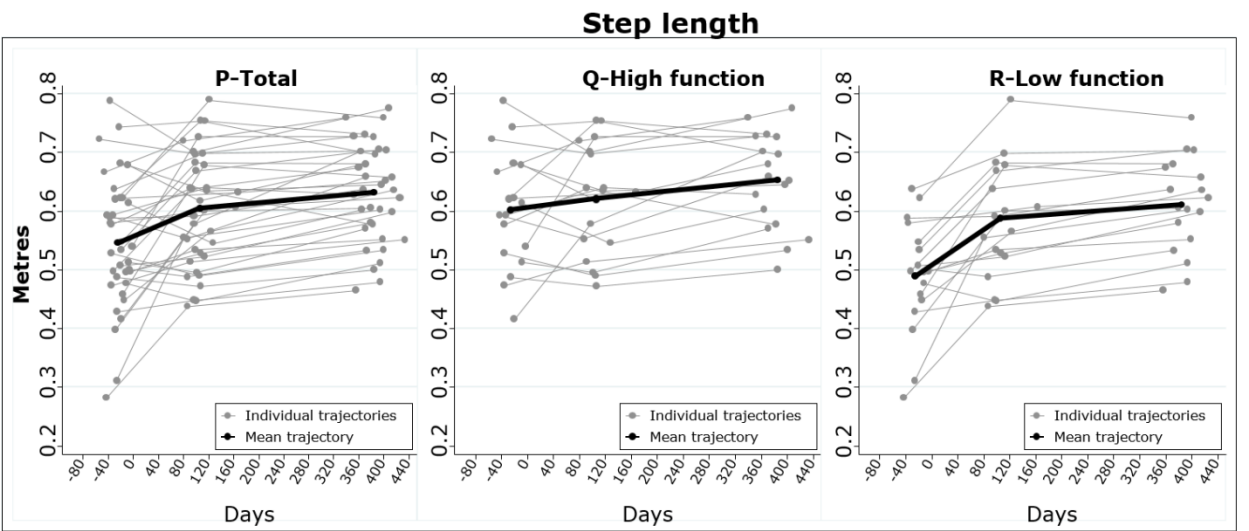
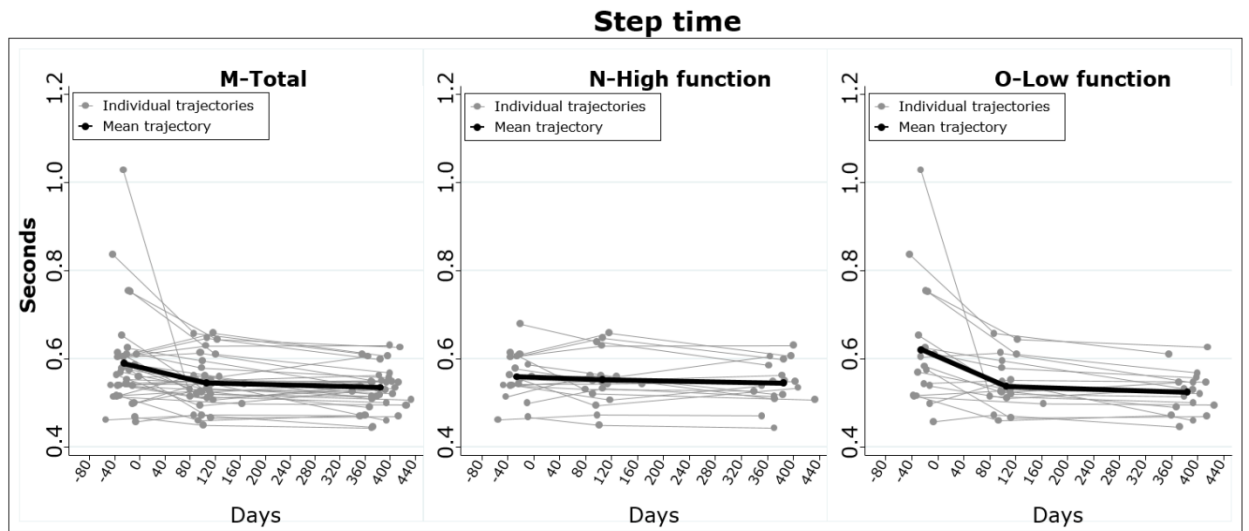
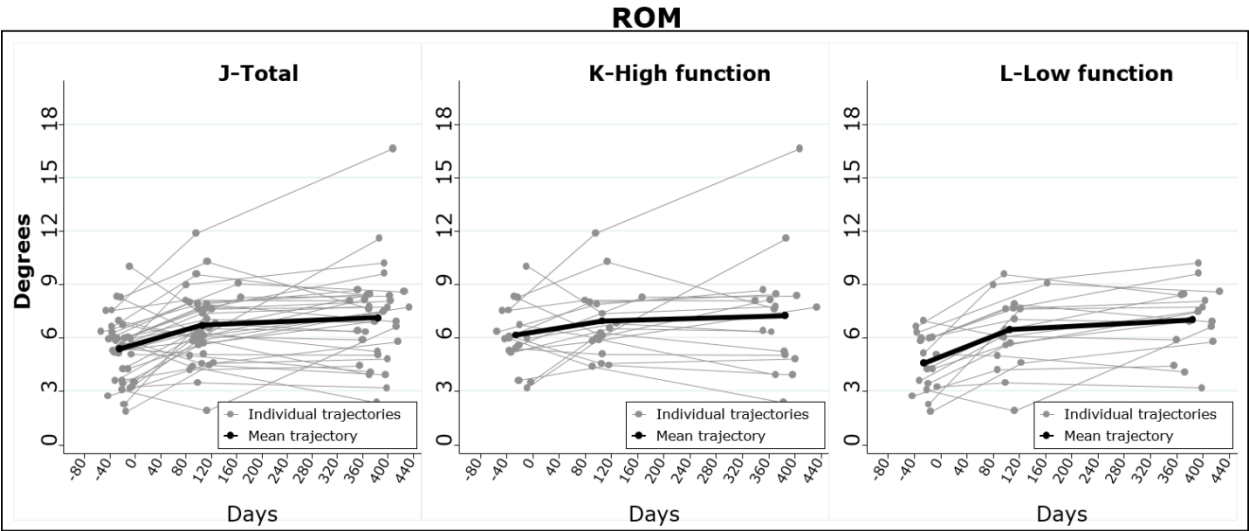


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Cadence



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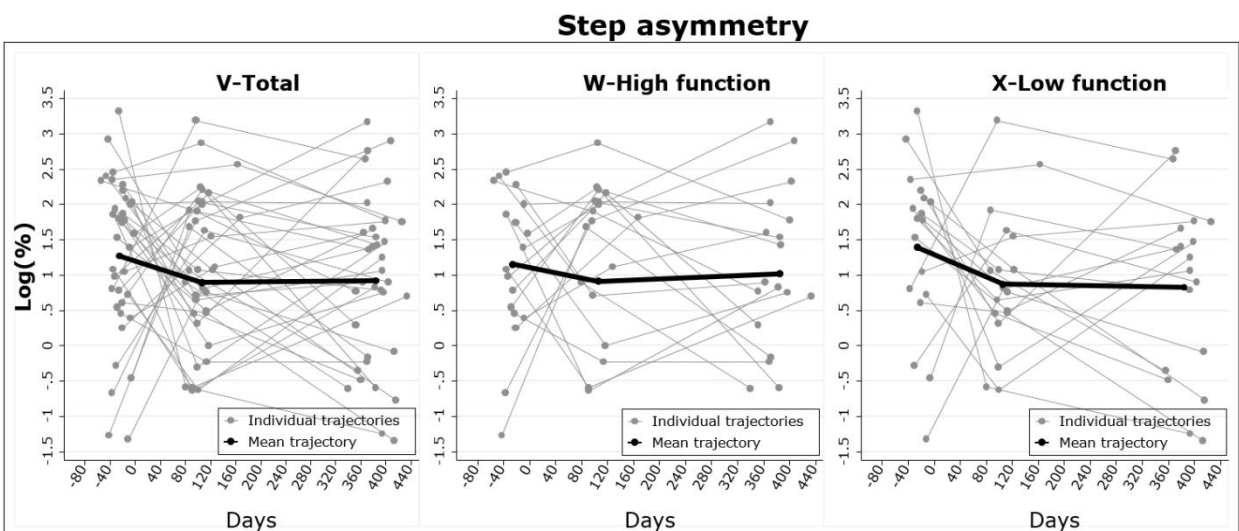
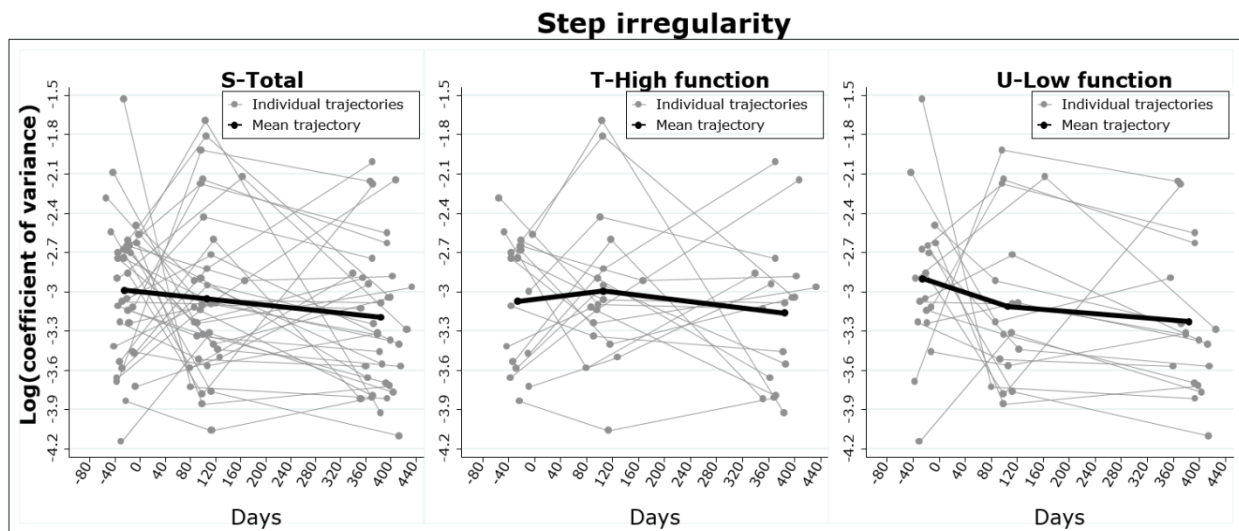


Figure 1, A-X: Individual (grey) and mean (black) trajectories for measures of WOMAC function score (A=total group, B=high function group, C=low function group), walking speed (D=total group, E=high function group, F=low function group), cadence (G=total group, H=high function group, I=low function group), ROM (J=total group, K=high function group, L=low function group), step time (M=total group, N=high function group, O=low function group), step length (P=total group, Q=high function group, R=low function group), step irregularity (S=total group, T=high function group, U=low function group) and step asymmetry (V=total group, W=high function group, X=low function group) during longitudinal follow-up.

Outcome parameters		Pre-operative		Low vs High	3 months			Low vs High	12 months			Low vs High	Control group n=30		
		Median	IQR	p-value	Median	IQR	p-value	p-value	Median	IQR	p-value	p-value	Median	IQR	p-value
WOMAC function (0-100)	Total	48.5	35.5-71.3		91.2	81-95.6	<0.001		95.6	83.8-100	0.44				
	Low function	35.5	22.1-41.1		90.9	79.4-95.6	<0.001		94.1	83.8-98.5	0.89				
	High function	71.3	64.7-82.4	<0.001	91.2	83.8-98.5	<0.001	0.53	96.3	85.9-100	0.24	0.44			
Speed	Total	0.97	0.81-1.12		1.12	0.96-1.30	<0.001		1.20	1.08-1.33	<0.001		1.29	1.14-1.41	0.036

(m/s)	Low function	0.89	0.71-0.97		1.10	0.92-1.30	<0.001		1.20	1.09-1.33	0.001		
	High function	1.10	0.97-1.24	0.006	1.16	0.98-1.36	0.28	0.45	1.23	1.07-1.34	0.055	0.69	
Cadence	Total	106.0	98.4-113.9		110.5	102.3-117.3	0.008		112.7	107.3-119.3	0.056		111.6 105.4-116.3 0.54
(steps/min)	Low function	103.8	92.0-116.3		113.7	100.8-117.7	0.007		114.4	109.8-122.5	0.069		
	High function	108.0	99.6-111.4	0.27	110.2	106.8-115.2	0.41	0.57	110.6	102.7-116.7	0.42	0.20	
Step time	Total	0.57	0.53-0.61		0.54	0.51-0.59	0.020		0.53	0.50-0.56	0.11		0.54 0.52-0.57 0.66
(s)	Low function	0.58	0.52-0.65		0.53	0.51-0.60	0.020		0.52	0.49-0.55	0.20		
	High function	0.56	0.54-0.60	0.27	0.55	0.52-0.56	0.48	0.57	0.54	0.51-0.59	0.35	0.20	
Step length	Total	0.54	0.48-0.62		0.60	0.53-0.68	<0.001		0.64	0.57-0.70	<0.001		0.68 .63-0.75 0.004
(m)	Low function	0.50	0.45-0.55		0.58	0.52-0.67	<0.001		0.61	0.55-0.67	0.001		
	High function	0.60	0.53-0.68	0.003	0.63	0.55-0.70	0.37	0.22	0.66	0.58-0.73	0.062	0.17	
ROM	Total	5.7	3.6-6.3		6.4	5.3-7.9	<0.001		7.5	5.5-8.4	0.014		7.3 5.9-8.9 0.12
(°)	Low function	4.7	3.2-6.0		6.3	5.0-7.7	<0.001		7.2	6.0-8.4	0.010		
	High function	6.0	5.3-7.5	0.015	6.4	5.8-8.0	0.10	0.57	7.7	5.0-8.4	0.051	0.97	
Step irregularity	Total	0.05	0.03-0.07		0.05	0.03-0.06	0.65		0.04	0.03-0.06	0.26		0.03 0.02-0.04 0.37
(CV)	Low function	0.05	0.04-0.07		0.04	0.03-0.07	0.40		0.04	0.03-0.06	0.44		
	High function	0.06	0.03-0.07	0.68	0.05	0.04-0.06	0.60	0.38	0.05	0.03-0.06	0.42	0.55	
Step asymmetry	Total	4.75	1.78-7.82		2.92	1.58-7.05	0.34		2.67	0.88-5.51	0.93		3.28 1.81-5.77 0.87
(%)	Low function	5.97	2.05-8.00		2.20	1.58-4.67	0.28		3.18	0.70-5.23	0.88		
	High function	3.46	1.58-7.45	0.47	5.99	2.03-7.69	0.71	0.15	2.38	1.34-5.92	0.85	0.66	

Table 1: Outcomes of WOMAC function score and gait parameters for the total patient group and sub groups with a low pre-operative

WOMAC function score (below median) and a high pre-operative WOMAC function score (above median). IQR= interquartile range.

	WOMAC function score					
	pre-operative		3 months		12 months	
	r	p-value	r	p-value	r	p-value
Speed	0.51	0.002	0.31	0.071	0.45	0.005
Cadence	0.31	0.062	0.24	0.158	0.37	0.027
Step time	-0.31	0.062	-0.24	0.158	-0.37	0.027
Step length	0.47	0.004	0.25	0.134	0.32	0.059
ROM	0.43	0.010	0.14	0.422	0.51	0.002
Step time irregularity	-0.06	0.717	-0.26	0.119	-0.39	0.018
Step time asymmetry	-0.11	-0.530	0.06	0.741	-0.33	0.047

Table 2: Spearman correlation coefficients (r) between WOMAC function score and gait parameters with corresponding p-values.

Averaged change per month		Pre-operative – 3 months			Low vs High	3 months – 12 months			Low vs High
		Mean	CI (95%)	P-value	P-value	Mean	CI (95%)	P-value	P-value
WOMAC function score (0-100)	Total	8.45	6.36 - 10.54	<0.001		0.17	-0.26 - 0.59	0.44	
	Low function	13.31	11.08 - 15.55	<0.001		-0.039	-0.62 - 0.54	0.89	
	High function	3.59	2.10 - 5.08	<0.001	<0.001	0.37	-0.25 - 1.00	0.24	0.34
Speed (m/s)	Total	0.035	0.016 - 0.055	<0.001		0.008	0.004 - 0.012	<0.001	
	Low function	0.060	0.030 - 0.091	<0.001		0.008	0.003 - 0.013	0.001	
	High function	0.011	-0.009 - 0.030	0.28	0.007	0.008	0 - 0.014	0.28	0.86

Cadence (steps/min)	Total	1.50	0.39 - 2.60	0.008		0.24	-0.01 - 0.49	0.056	
	Low function	2.64	0.71 - 4.58	0.007		0.35	-0.03 - 0.73	0.069	
	High function	0.35	-0.48 - 1.17	0.41	0.03	0.13	-0.19 - 0.45	0.42	0.39
Step time (s)	Total	-0.010	-0.002 - -0.019	0.02		-0.001	-0.002 - 0	0.11	
	Low function	-0.019	-0.035 - -0.003	0.02		-0.001	-0.004 - 0.001	0.19	
	High function	-0.002	-0.003 - 0	0.48	0.039	-0.001	-0.003 - 0.001	0.35	0.67
Step length (m)	Total	0.013	0.006 - 0.02	<0.001		0.003	0.001 - 0.004	<0.001	
	Low function	0.023	0.013 - 0.033	<0.001		0.002	0.001 - 0.004	0.001	
	High function	0.004	-0.005 - 0.014	0.37	0.009	0.003	0.001 - 0.006	0.012	0.57
ROM (°)	Total	0.31	0.16 - 0.45	<0.001		0.046	0.015 - 0.108	0.014	
	Low function	0.43	0.25 - 0.62	<0.001		0.059	-0.012 - 0.129	0.010	
	High function	0.18	-0.04 - 0.40	0.10	0.08	0.034	0.068 - 0.137	0.051	0.70
Step irregularity log(cv)	Total	-0.015	-0.08 - 0.05	0.65		-0.015	-0.04 - 0.01	0.26	
	Low function	-0.049	-0.164 - 0.056	0.40		-0.012	-0.043 - 0.019	0.44	
	High function	0.019	-0.051 - 0.088	0.60	0.32	-0.018	-0.062 - 0.026	0.42	0.82
Step asymmetry log(%)	Total	-0.086	-0.263 - 0.091	0.34		0.003	-0.062 - 0.068	0.93	
	Low function	-0.118	-0.334 - 0.098	0.28		-0.005	-0.069 - 0.059	0.88	
	High function	-0.055	-0.341 - 0.232	0.85	0.73	0.011	-0.104 - 0.125	0.85	0.81

Table 3: Averaged change per month during the first 3 post-operative months and the following 9 post-operative months, comparing the low function group with the high function group. CI=confident interval.

4. Discussion

The primary aim of this study was to compare physical function after THA between patients with a low and high self-reported level of pre-operative physical function, by subjective self-reported WOMAC function scores and objective inertial sensor based gait analysis. Although it has been demonstrated that the post-operative outcomes of patients with lower pre-operative WOMAC function scores do not improve to the same magnitude as patients with higher pre-operative scores [8], it was hypothesized that these differences in functional outcome may not be found with objective measures of gait. To address this hypothesis, the study's cohort was divided into a low and a high function group using the median of the pre-operative WOMAC function score (i.e. 49) as a cut-off. These self-reported levels of physical function are in comparison with the findings of previous studies by Unnanuntana et al. [23] and Mahomed et al. [35] which reported mean pre-operative WOMAC function scores of 48.5 and 46 respectively in their cohorts of pre-operative THA patients. In the current study, patients with lower pre-operative WOMAC function scores also performed significantly worse on gait pre-operatively; they walked slower, with smaller steps and less

ROM. However, only weak to moderate correlations (Spearman's r range 0.43-0.51) were found between pre-operative WOMAC function scores and pre-operative gait parameters. These findings concur with the results from the study by Unnanuntana et al. [23], which reported a Spearman's correlation coefficient of 0.54 between pre-operative WOMAC function scores and a 2-minute walk test. Findings from our study and previous research suggest that WOMAC and gait capture a different dimension of physical function. Our study's main finding was that the significant differences in pre-operative WOMAC function scores and gait parameters between low and high function groups are not found at 3 and 12 months after THA. Patients with a low pre-operative level of physical function seem to experience more functional limitations in relation to OA and have more functional improvement to gain from surgery. Post-operatively, they improve significantly more on both subjective self-reported WOMAC function scores and objective gait parameters, and reach mean functional outcomes comparable to patients with better pre-operative function. Therefore, in the analysis of functional recovery after THA, our findings suggest that it is important to differentiate a cohort into subgroups and look at the relative changes instead of focusing solely on absolute changes. In addition, our findings on functional recovery after THA are in marked contrast to pain based outcomes, where a pre-operative score is usually a strong predictor of post-operative outcome [9, 10]. Composite pain and function scores behave like pain scores in predicting outcome [10] which argues for pain and function to be measured separately as distinct domains.

The second aim of this study was to compare the trajectories of post-operative recovery between WOMAC function scores and gait parameters and it was hypothesized that WOMAC function scores would demonstrate a larger change in the first 3 months and a smaller change in the following 9 months due to ceiling effects. A ceiling effect occurs when the test is relatively easy and a substantial proportion of participants reach either maximum or near-maximum scores [12] and when this proportion is larger than 20% at one occasion during longitudinal follow-up [11]. In this study's cohort, 18 of 36 patients (50%) reached near-maximum (≥ 90) WOMAC function scores at 3 months post-operatively, 23 of 36 patients (64%) reached near-maximum (≥ 90) WOMAC function scores at 12 months post-operatively and 10 of 36 patients (28%) reached the maximum score (i.e.100) at 12 months post-operatively. Due to this ceiling effect, further functional improvement will not be captured by the WOMAC function score and the true extent

of a patient's functional abilities cannot be determined. In contrast, objective measures of function by gait analysis demonstrated sensitivity to post-operative improvement beyond 3 months follow-up for three main gait parameters (i.e. speed, step length and ROM); but no further improvements were found for cadence, step time, asymmetry and irregularity. Moreover, the observed improvement of gait parameters between pre-operative status and 3 months after THA, was only found in patients with a low pre-operative function and between 3 and 12 months after THA only step length demonstrated a significant improvement in the high function group. For step time irregularity and step time asymmetry, the lack of significant differences may be due to inaccuracy of the algorithm to measure heel strike events precisely, as literature reports mean errors of 13ms (SD= 35ms) for heel strike measurements with this specific algorithm compared to force plate measurements [29]. Furthermore, the small subgroup size (n=18) may lack power for the minor gait improvements observed in the high function patient group to become statistically significant. Another explanation for the lack of significant post-operative changes for gait parameters in the high function group could be that gait is a low demand task in comparison to other activities of daily living, which may be better discriminators of outcome for those with high pre-operative function. Normal gait is also a main rehabilitation goal in the early post-operative stage, therefore practiced extensively and thus likely to improve quickly [32]. Challenging physical tasks may have higher sensitivity as a tool to identify remaining functional disabilities post-operatively [36]. For gait, variation of walking speed (e.g. preferred speed vs. high speed) could provide a bigger challenge [37]. Other physically more demanding performance-based tests, such as timed get-up-and-go (TUG), six minute walk test (6MWT) and stair climbing test (SCT) could be used as an alternative to the objective functional test described in this study [38, 39].

The third aim of this study was to compare the outcomes of gait analysis one year after THA from our cohort with those of a healthy control group without lower limb OA or previous lower limb surgery, and we hypothesized that gait performance after THA would still be slightly worse than in healthy controls [25]. Our results demonstrated that by 12 months post-operatively, patients with a THA had nearly reached the level of the control group in gait performance, except for the parameters speed and step length. At 12 months after THA, patients seem to walk with a similar step frequency compared to healthy controls but with smaller

steps and consequently lower speed. These findings are in accordance to the results of a meta-analysis by Ewen et al. [40] including 7 studies comparing gait between patients >6 months after THA and a control group. Across these studies, the mean walking speed for the patient groups and control groups ranged from 0.707–1.31 m/s and 0.921–1.34 m/s respectively, and 3 studies reported significantly lower walking speed for their patient group compared to their control group. Furthermore, 6 studies reported stride length and 4 of these studies reported a significant reduction in stride length for their patient group compared to their control group. A more recent systematic review by Kolk et al. [25] describes the results from 28 studies comparing gait between patients after THA and a control group, including the 7 studies from the meta-analysis by Ewen et al. [40], and demonstrates that walking speed was not different from controls in most studies that had a short (6-9 months) follow-up period, whereas it was lower than controls in most of the studies that had a follow-up of 24 months or longer. This coincided with a reduction in step length in the long-term follow-up studies, which was generally not found in the short-term follow-up studies. In our current study, the patient group demonstrated a median walking speed of 1.20m/s at 12 months follow-up which was significantly lower than our control group with a median walking speed of 1.29m/s ($p=0.036$). Furthermore, step length was also significantly reduced in our patient population at 12 months follow-up compared to our control group (0.64m vs. 0.68m; $p=0.004$).

Limitations of the study should be acknowledged when interpreting the results. Although the inclusion of multiple assessment times is a strength, the assessment of function at 3 and 12 months post-operatively may not capture the full extent of post-operative changes in physical function. As most of the functional improvement was demonstrated within 3 months post-operatively for WOMAC function scores and for gait parameters, earlier follow-up measures (e.g. six weeks post-operatively) could provide more insight in recovery and guide early individual rehabilitation [17]. In order to capture improvement of physical function beyond 12 months post-operatively and in patients with high pre-operative function, we advocate combining gait analysis with more high demand tasks. Another limitation of our study is the small sample size and, as with any prospective cohort study, missing data. Only patients undergoing primary THA were included in the analysis and patients that did not complete all the assessments were excluded. Consequently, our small

study population limits the conclusions that can be drawn. However, the study was exploratory in nature and generated findings that can be investigated further.

5. Conclusion

This study indicates that in a cohort of patients undergoing THA, pre-operative differences in mean WOMAC function scores and gait parameters between low and high function subgroups have disappeared by 3 months post-operatively. Therefore, it may be important to look at the relative changes rather than the absolute changes only. Furthermore, assessment of physical function by self-report showed marked improvement in the first 3 months after surgery with little further improvement thereafter, whereas gait analysis showed a more gradual improvement over 12 months with sensitivity to capture improvement beyond 3 months after THA. The weak to moderate correlations between both methods suggest that they measure slightly different aspects of functional recovery and can be supplementary to each other.

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